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Pulsed Eddy Current Technology: Characterizing Material Loss with Gap and Lift-off Variations

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Abstract. Ownership costs of operational aircraft have increased steadily over the years. One of the major cost drivers is structural deterioration due to corrosion. Beyond the economics, finding and characterizing corrosion is essential for the continued airworthiness of aircraft fleets. To this end, the pulsed eddy current technique holds the potential of becoming the primary means of detecting corrosion in multilayered structures. Its wide-band frequency spectrum allows the determination of a large number of parameters, such as defect size and location. Pulsed eddy current is still considered an experimental nondestructive technique because of realistic inspection problems (e.g., probe tilting, protrusion of rivets, and thickness variations in adhesive and paint) have not been addressed in the past. Recent advances change this situation and allow pulsed eddy current to be a credible field technique.

Introduction

Aging commercial and military aircraft fleets pose new challenges to engineering authorities responsible for granting and ensuring airworthiness. As aircraft structures age, corrosion becomes one of the largest drivers in life-cycle costs [1] and is a primary causal factor in a substantial number of safety incidents and accidents [2]. These premises, combined with the coming of corrosion-tolerant airframe designs, justify the efforts made to detect, characterize, and quantify corrosion in aircraft structures. Several nondestructive testing techniques lend themselves to these tasks. In the aerospace industry, visual inspection remains the primary means for detecting corrosion in fuselage multilayered aircraft structures, such as lap splices. This method detects the surface deformations that arise between the rivets (i.e., pillowing) due to the increased volume of the corrosion products between the plates, however, deformations not due to corrosion, such as poor quality control during manufacture or previous repairs, can give false indications. In addition, as corrosion becomes more of a structural integrity issue, there is the need for quantitative assessment capabilities in nondestructive evaluation. Radiography testing, ultrasonic testing, thermography, and most other nondestructive testing (NDT) techniques can also be used for corrosion detection, however, they exhibit limitations for the inspection of multilayer structures. The notable exception is pulsed eddy current (PEC).

which has been found to be the method of choice for characterizing corrosion in multilayer structures in two independent studies conducted by the U S National Research Council [3] and the North American Technology and Industrial Base Organization [4]

Like other NDT techniques, most PEC instruments have some limitations In fact, previous instruments rely on a constant probe–workpiece spacing (i e , lift-off) This requirement stems from the fact that lift-off variations associated with normal paint thickness variations or small variations in fastener head protrusion on a typical aircraft skin were causing changes to the flaw signal, thus leading to erroneous results This restriction severely limits any "field" application of pulsed eddy current for corrosion detection in aircraft structures Fortunately, recent advances in pulsed eddy current technique have shown the ability to detect, characterize, and quantify material loss in multilayered structures without negative impact from practical problems such as protruding rivet heads, surface warping, dents, and variation in paint and gap thicknesses It is therefore possible to take advantage of the shorter inspection time and the ease of acquisition of data associated with this technology

Background

Conventional eddy current (EC) instruments employ harmonic continuous-wave excitation at only one or a few discrete frequencies On the other hand, pulsed eddy current (PEC) instruments apply a broad-band pulse, or step excitation, to a coil to generate a magnetic field pulse. This magnetic field pulse propagates into the material, generating pulsed eddy currents that oppose the changing incident field [5] The net field, which is the sum of the incident field and the field "reflected" by the specimen due to the induced eddy currents, can be detected by a coil.

Conventional EC and PEC instruments provide different measurements. Conventional EC instruments measure the impedance and reactance of the detection coil, while the PEC instrument measures the voltage transient response The main advantage of the PEC instrument is that it yields a transient signal with a frequency spectral content going from DC to 100 kHz or higher This broad-band characteristic provides the ability to conduct digital signal analysis and extract subtle differences in the waveform associated with small geometric variations, hence, it provides the ability to quantify a large number of parameters.

Most of the transient signal is caused by dispersion in the material and remains constant. It is therefore customary to ignore this gradient and subtract it by signal processing. This process is referred to as "balancing." One particular way to perform balancing is to subtract a reference signal from the total transient response As long as the transducer is moved over regions similar to that of the reference, a zero transient signal will be measured. If the transducer is moved over a flaw or other geometric feature, the transient can be associated with that condition [6] For example, material loss at or near the surface will have more effect on the early-time portion of the total transient interval than on the late-time portion. The opposite will be true for very deep defects

Three features of the balanced transient signal (Fig 1) are most often employed to quantify the defect peak amplitude, time to peak amplitude (TPA), and time to zero crossing (TZC) [6–9] The magnitude of the peak amplitude is proportional to the amount

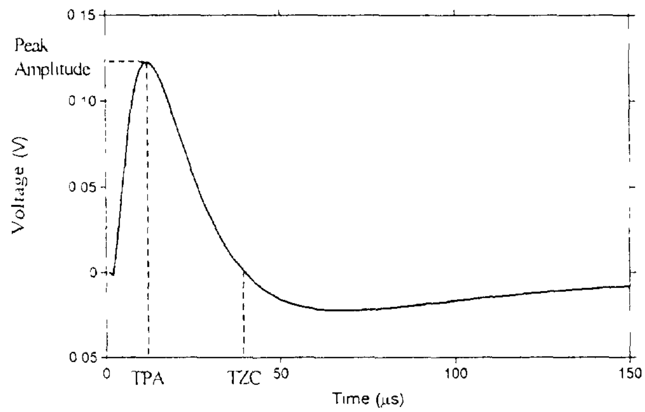


Fig. 1. Balanced transient response

of metal loss. In fact, it depends on the position and size of the defect. The time to peak amplitude, the arrival time of this peak, is related to the filtering of the magnetic field by the sample and the position of the flaws. In this case, there is not a linear relationship between distance of propagation and arrival time of the peak of the transient signal. Nonetheless, the trend is sufficiently dominant to make it a useful tool for analyzing the variation of a structure with depth [10] The last feature used by researchers is the time to zero crossing This feature provides an indication of the location of the defect and the condition of the test object.

Even though the presence of subsurface flaws and discontinuities is determined by comparing the transient signal for a flaw-free reference structure with the signal produced for the structure being inspected, factors that are not generally controlled during the manufacture of aircraft structure can substantially alter the electromagnetic environment presented by the structure being inspected and thus affect the transient response of the detection coil (e.g , an increase in the peak amplitude or an earlier time to zero crossing). For example, it is common practice to coat various portions of aircraft with paint or other protective material. Such coatings are generally nonconductive The change in coating thickness introduces a varying lift-off between the excitation/detection coils and the structure, even though physical contact is maintained between the coil and the coated surface of the structure being examined. As a result, the reference structure cannot generally be configured to present an electromagnetic environment identical to that of the inspected conductive region. Thus, examining only one or two parameters of the PEC transient response will likely not provide characterization of complex structures. It is necessary to examine the PEC transient signal over its entire transient interval in order to extract quantitative information with respect to small material loss within the structure

Experimental Procedure

The experimental setup consists of an XY positioning robot and a data acquisition system, both interfaced to a PC computer [11]. The software interface controls the motion and positioning of the robot as well as the data acquisition The capturing method of the transient response signal is based on a technique initially developed by Moulder et al [9] It consists of a circuit where the detection coil is in series with a resistor and the voltage drop across a resistor is fed into a low-noise amplifier, then digitized by a PC-based data acquisition board These signals contain the total information on both the incident and reflected field

The system can accommodate several probe–coil configurations, however the best results were obtained with reflection probes, also referred to as concentric driver-pickup coils The probes can be optimized for the specimens tested The coils are built to have a specific frequency response The selection of the frequency depends on the thickness of the multilayered structure to be inspected, i e , thicker structures require probes with lower inspection frequencies

Experimental measurements were made for two types of test specimens One type was used to develop the PEC technique For this activity, the calibration test specimens were machined with material losses to simulate corrosion The specimens were two-layer systems composed of 2024-T3 aluminum alloy, both layers nominally 1 mm in thickness These plates could be assembled to simulate material losses at the bottom of the top plate (BoT), the top of the bottom plate (ToB), and the bottom of the bottom plate (BoB) In order to capture data for gap variations (i e , variations in interlayer spacings), a vacuum system was used in conjunction with plastic spacers Spacers were arranged to simulate gap variations from 0 0 to 0 4 mm at 0 1-mm increments between the first and second plates. The second type of specimen used for the experiments was a two-layer, riveted lap splice composed of plates 1 mm thick made of 2024-T3 aluminum This assembly was placed in a corrosion chamber to initiate crevice corrosion This specimen was considered representative of a lap splice since it exhibits the traditional surface deformation due to the corrosion products between the rivets Hence, this specimen was used to validate the results obtained with the calibration test specimen

Results

Quantifying Material Loss versus Alleviating Lift-off Effects

The balanced transient signal is the traditional signal used for determining the presence, the amount, and the location of corrosion, however, an increase in the lift-off distance increases the balanced transient peak amplitude advances its location, and advances the time to zero crossing (where applicable) to such an extent that defect size and location cannot be adequately determined by these traditional features The effect of lift-off is clearly shown in Fig 2b The defects identified in Fig 2a are effectively undetected with the peak amplitude feature In effect Fig 2b simply projects the variation of the surface topography due to the surface warp that caused very slight probe tilt variations that reduced its coupling during the inspection In an effort to overcome this drawback, previous research [12] has demonstrated that one particular feature, the lift-off point of intersection (LOI), did not vary significantly with variation in coupling or increase in probe lift-off The lift-off point of intersection C-scan (Fig 2c) clearly demonstrates the ability of this feature to detect material loss in the multilayer structure From this figure, it is also intuitively possible to quantify the material loss.

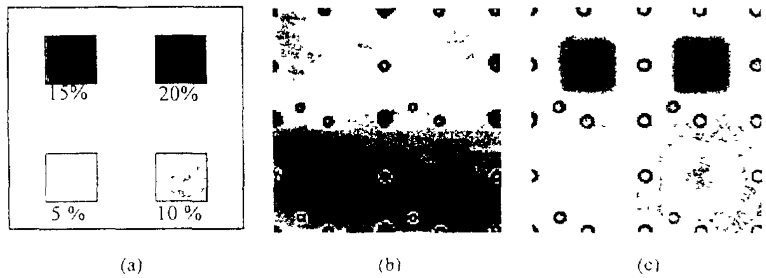


Fig. 2. Qualitative assessment of material loss (a) test specimen schematic, (b) peak amplitude C-scan results, (c) lift-off point of intersection C-scan results

Determining the location of the lift-off point of intersection is relatively simple First, one can select any area of the structure to be inspected. A calibration sample could also be used for this purpose. Then, for a given location, one can record at least two but preferably three transient responses where only the transducer lift-off distance is varied The time at which the three lift-off balanced transient responses intersect is the lift-off point of intersection (Fig 3) If the test sample has material loss, the voltage amplitude at the lift-off point of intersection will vary from the value measured for no defect. It is therefore possible to positively ascertain the presence of corrosion in a multilayer structure independently of lift-off variations. Also, by using a calibration specimen, it is possible to generate a look-up table providing voltage amplitudes versus material loss.

Applying these findings to a real specimen yields the following results. To simulate lift-off variations, layers of adhesive tapes were placed to introduce lift-off in a particular region of the scan Figure 4 shows the C-scan results obtained for the peak amplitude The lift-off is clearly visible in the vertical strip located between 85 and 135 mm On the other hand, results obtained at the lift-off point of intersection (Fig 5) show the elimination of the noise introduced by the variation in lift-off. Defect size can be ascertained via look-up tables previously generated using a calibration specimen [13].

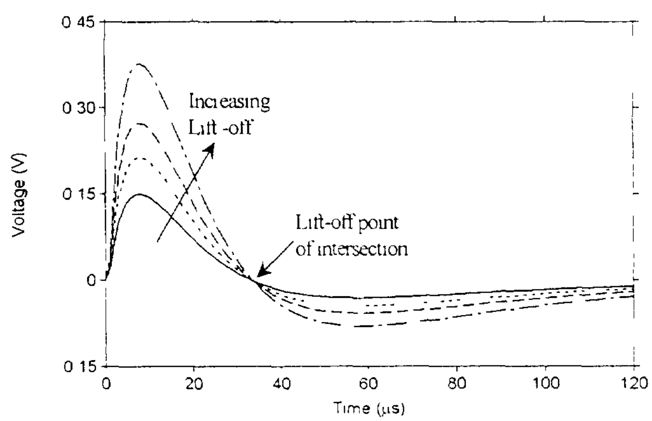


Fig. 3. Determining the location of the lift-off point of intersection

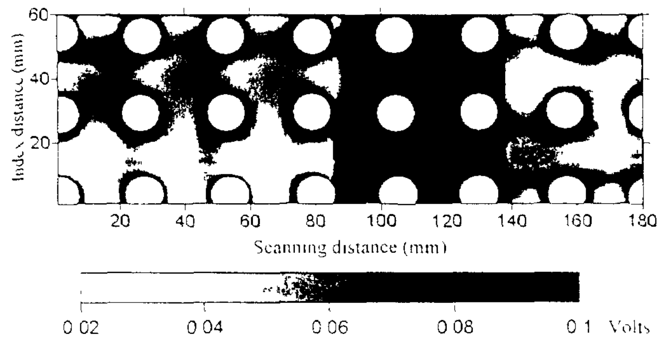


Fig. 4. Peak amplitude C-scan (rivets are blanked to facilitate comparison)

Quantifying Material Loss versus Alleviating Gap and Lift-off Effects

Results obtained at the lift-off point of intersection are affected by another source of noise, variation of the gap between plates in the multilayer assembly Specifically, a specimen with no defect but with larger gap than the nominal value (Fig. 6a) will show as a defect in a lift-off point of intersection C-scan (Fig. 6b). To alleviate this type of false indication, one has to use a feature capable of assessing material loss independently of gap variations. Such a feature exists and will be referred to as the gap point. As shown in Fig. 6c, the gap point allows measurements that do not vary significantly with variations in gap thickness, however, the gap point is sensitive to lift-off variations (Fig 7) Thus, its use is contingent on the ability to compensate the signal for lift-off variations

Lift-off compensation attempts to reverse the effects of variations in probe lift-off, so as to restore the transient response observed at each point to the signal which would have been observed in the absence of the lift-off variation The lift-off compensation gets its information directly from the balanced transient response In fact, the early part of the signal provides the ability to determine lift-off, as shown in Fig 8

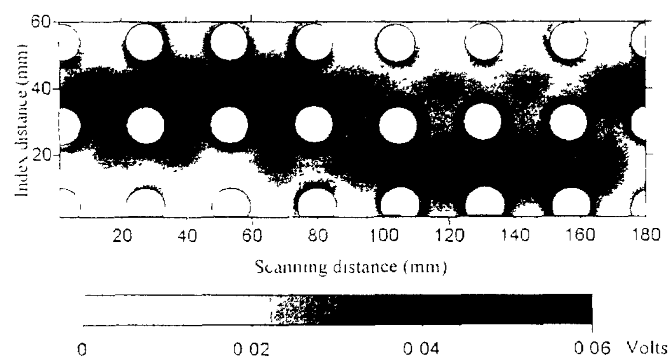
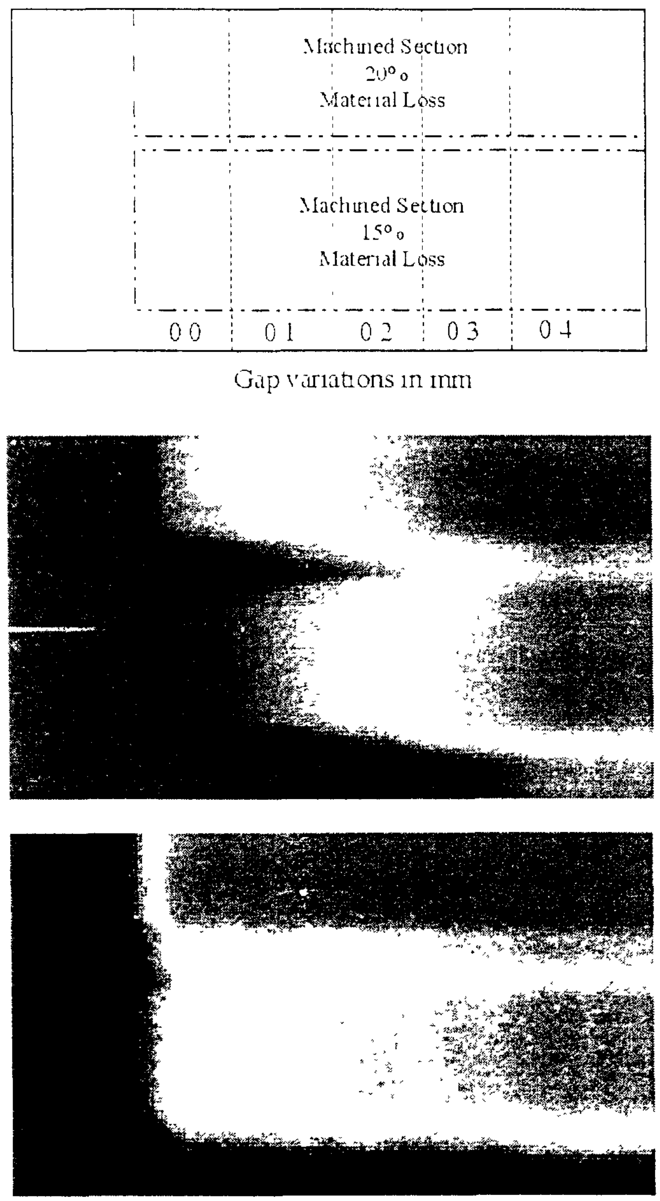


Fig. 5. Lift-off point of intersection C-scan (rivets are blanked to facilitate comparison)

(a)



(b)

(c)

Fig. 6. Variation of the gap thickness and the ability to quantify material loss (a) test specimen schematic, (b) LOI C-scan results, (c) gap-point C-scan results

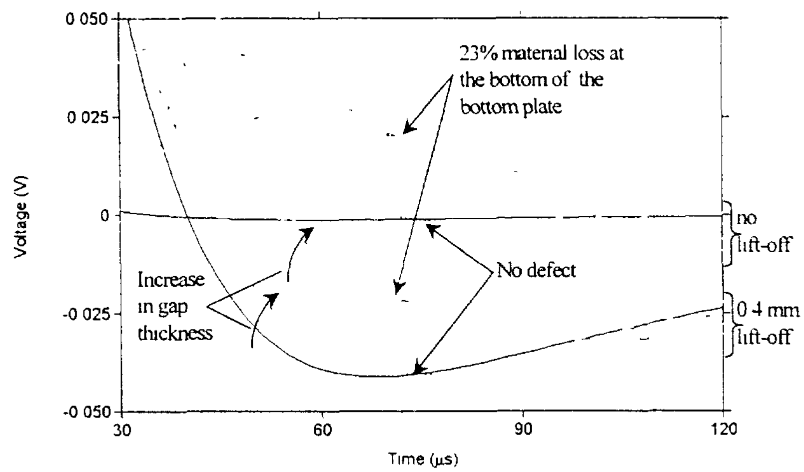


Fig. 7. Composite graph of balanced transient responses for lift-off, defect, and gap variations showing the effect of lift-off on the gap point.

Applying these findings to a real specimen yields the results shown at Fig. 9. To simulate lift-off variations, layers of adhesive tape were placed on the specimen. The layers of tape increased the lift-off distance by 0.189 mm. Figure 9a shows the C-scan results obtained for the gap point without lift-off compensation. The lift-off is clearly visible in the vertical strip located between 85 and 135 mm. In addition, the lift-off effects due to surface pillowing are evident. On the other hand, Fig. 9b shows the gap point C-scan with lift-off compensation. The lift-off compensation eliminates the noise introduced by the variation in lift-off. Defect size can also be ascertained via this feature. Through the use of calibration standards, it is possible to determine the voltage value at the gap point for various defect sizes and generate a look-up table In effect, the voltage

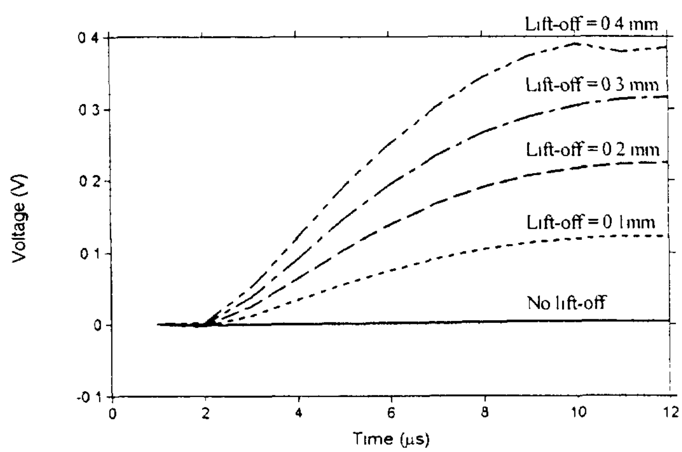


Fig. 8. Effect of lift-off variations on the transient responses for an unflawed area

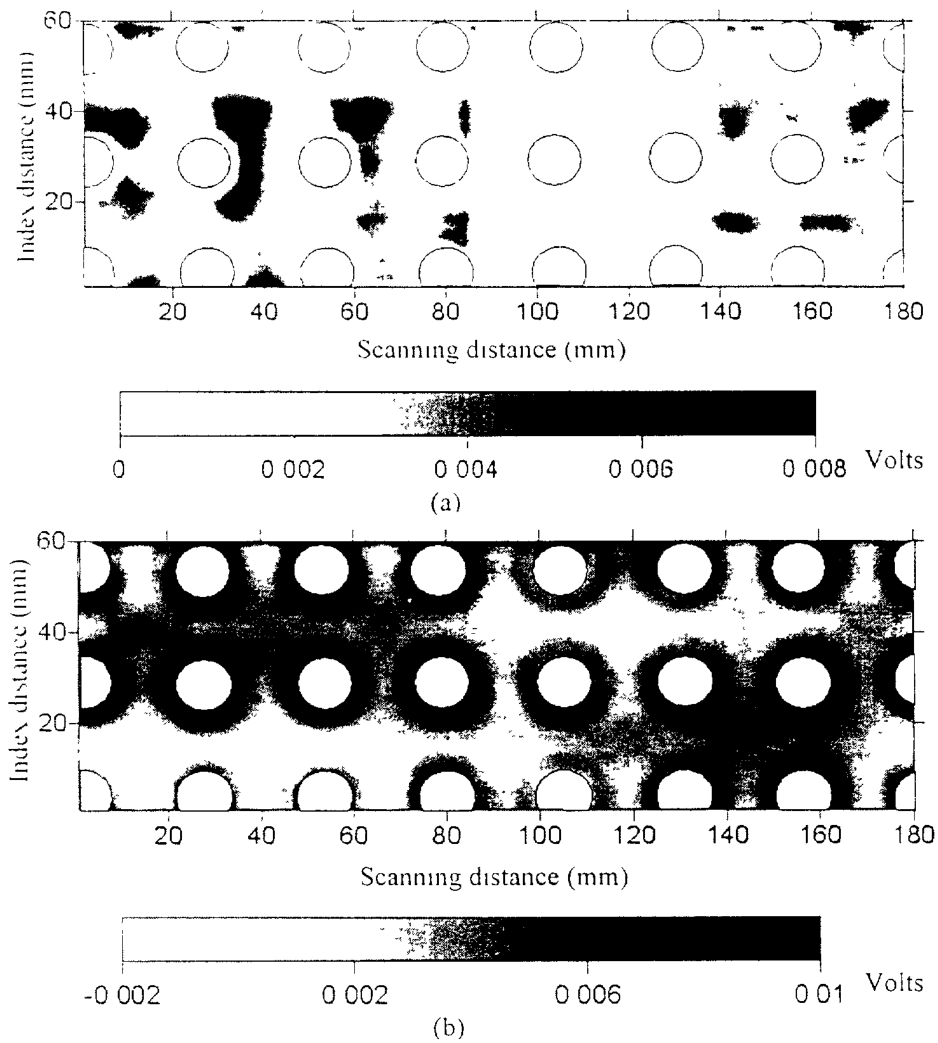


Fig. 9. (a) Gap point without lift-off compensation (b) gap point with lift-off compensation (rivets are blanked to facilitate comparison)

amplitude at the gap point varies from the value measured for no defect This feature has great potential, but finding the gap point during an inspection is not a trivial task It can only be found by using a specifically designed calibration block representative of the structure under inspection

The results shown at Figs 5 and 9b are comparable The main differences are due to variation in gap between the plates Combining the results obtained by the LOI and the gap point could yield the gap thickness, however, further research will need to take place to prove this capability

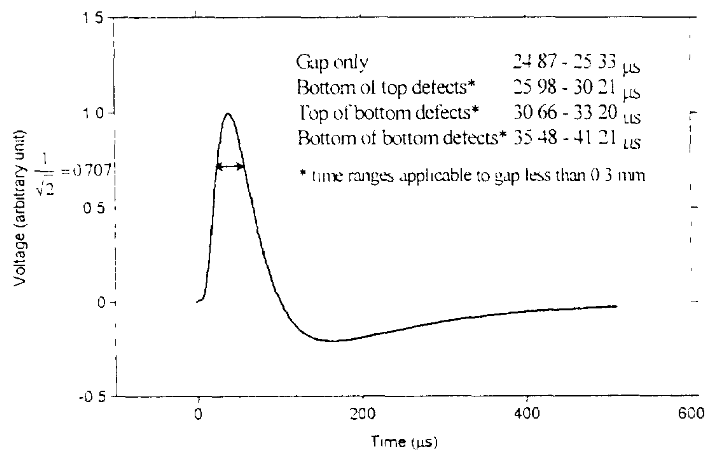


Fig. 10. PEC ability to determine defect location via the half-power width

Determining the Location of Material Loss in a Multilayer Specimen

The characterization of material loss would not be complete if the location could not be ascertained. Previous research [13] showed the ability to determine the location of material loss in a multilayer structure Effectively, the half-power transient response width (Fig. 10) provides the information pertaining to defect location given a constant lift-off. Hence, it is necessary to compensate for lift-off. For this case, compensation was achieved by simply subtracting the transient response due to lift-off only and normalizing the corrected transient response to facilitate the determination of the half-power width. This method provided time ranges for defects found at various locations in the two-layer assembly

Conclusions

Pulsed eddy current has the ability to quantify material loss and determine the defect location in conductive multilayered structures, such as lap splices The pulsed eddy current technique can be performed under field conditions because of its ability to detect, characterize, and quantify material loss in multilayered structures without negative impact from practical problems such as protruding rivet heads, surface warping, dents, and variation in paint and gap thicknesses It brings new capabilities that will likely play a major role in supporting the requirements for corrosion-tolerant aircraft designs

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